33-777

1

Today

- Historical Perspective
- The Milky Way
- The ISM

- Historical Perspective

Before we move on to discuss our modern understanding of galaxies and the Universe, it is worth reviewing the history of our understanding of the Universe.

It is obvious that stars in the sky are not distributed isotropically. Obvious to the naked eye, the Milky Way forms a band of light and dark patches across the sky. In 1610, Galileo resolved the MW into individual stars. Remarkably, it is not until the 20th century that astronomers understood the rough size of the Milky Way and the position of the Sun within it.

Our understanding of the Milky Way was driven by a few individuals.

- William Herschel
- Jacobus Kapteyn
- Harlow Shapley
- Edwin Hubble

Early studies by Herschel and Kapteyn were based on star counts. The basic idea was to count the number of stars in various directions brighter than some limiting magnitude, m. For a star with intrinsic absolute magnitude M, given m, the maximum distance it could be observed out to would be,

$$d = 10^{1+0.2(m-M)} \text{ pc}$$

For argument's sake, if we assume all stars have a similar absolute magnitude, M, and the stars within the MW are distributed uniformly, then the number of stars in a certain direction (within a solid angle) should scale as,

$$N \propto d^3$$

The number of stars as a function of limiting magnitude is then,

$$N(m) \propto 10^{0.6m}$$

This should hold until the edge of the system is reached.

Both Herschel and Kapteyn used this type of argument to show the MW must be a disk with the Sun near the center.

Harlow shapley conducted a similar argument using globular clusters instead of stars. He found that globular clusters are more abundant towards Sagittarius. If globular clusters are also part of the Milky Way he found that the MW must be much larger with the sun significantly offset from the center.

With the advent of better telescopes and photographic plates which could be used to take long exposures, arguments over the nature, size of the Millky way, and extent of the Universe heated up. This came to a head in the Great Debate.

- The Interstellar Medium

Up to this point in our discussion of stars we have effectively ignored the space between stars. It turns out that this "space" inside galaxies is not empty. The interstellar medium (ISM) is composed of gas:

- cold ($T \lesssim 300$ K)
- warm ($T \sim 10^4$ K)
- hot ($T \sim 10^6$ K)

Mostly hydrogen and helium. The ISM is enriched with metals from AGB stars and supernovae. Many of these metals are locked up in molecules astronomers call dust. The types of molecules that form in the ISM is an active area of research, but likely includes:

- graphite
- silicates (Si-O, Si-O-Si, etc)
- Polycyclic Aromatic Hydrocarbons (PAHs)
  ↳ ring-like molecules of C-C and C-H bonds

Observationally, a dusty ISM has some important consequences. As light is emitted from the surface of a star, it is scattered off dust particles in the ISM. This causes:

1. Extinction
2. polarization

of light rays from the source and:

3. reflection
4. emission

from the ISM itself.

Let's first focus on dust extinction. In general the intensity observed from a source (e.g. star) will be decreased by the presence of dust in the intervening ISM. In addition this extinction increases as the wavelength of light decreases between the infrared to the UV.

The dust extinction along a given line-of-sight to a source can be described in terms of the optical depth to the source.

$$I_\lambda = I_{\lambda,0}\, e^{-\tau_\lambda}$$

intensity of source in the absence of dust extinction

We can relate this to the observed magnitude of a source by considering the change in apparent magnitude attributed to dust

$$\Delta m_\lambda = m_\lambda - m_{\lambda,0} = -2.5\log\left(\frac{I_\lambda}{I_{\lambda,0}}\right)$$

$$= -2.5\log\left(e^{-\tau_\lambda}\right)$$

$$= 1.086\,\tau_\lambda$$

From this we can define the magnitude of extinction

$$A_\lambda = 1.086\,\tau_\lambda$$

The observed apparent magnitude is then given by,

$$m_\lambda = M_\lambda + 5\log\left(\frac{d}{pc}\right) - 5 + A_\lambda$$

In general extinction is wavelength dependent. This dependance is often quantified via an empirical extinction law

$$K(\lambda) \equiv \frac{A_\lambda}{E(B-V)} \equiv R_V \frac{A_\lambda}{A_V}$$

Here $E(B-V)$ is called the "color excess" and is defined as the difference in extinction in the two bands:

$$E(B-V) \equiv A_B - A_V$$

$$\Rightarrow R_V \equiv \frac{A_V}{E(B-V)}$$

For the professionals, note that this definition sometimes varies. For example

$$K'(\lambda) \equiv \frac{E(\lambda-V)}{E(B-V)} = K(\lambda) - R_V$$

In addition to dust extinction, the ISM also emits radiation. These are three particularly important processes that we should review:

1. H I emission
2. H II emission
3. dust emission

I will only mention the basics of these emission processes here. More quantitative discussions can be found in:

1. "Astrophysics for Physicists" Section 6.6
2. "Galaxy Formation and Evolution" sections 10.3.7 – 10.3.8

Neutral hydrogen (HI) in the ground state may emit or absorb photons with an energy corresponding to the spin-flip transition.

Since both the electron and proton have a spin and an associated magnetic dipole moment, there is a slight energy difference between the spin aligned and anti-aligned states.

spin aligned

anti-aligned

$$E_{\text{aligned}} > E_{\text{anti-aligned}}$$

$$\Delta E = 5.874 \ \mu eV$$

This energy difference corresponds to a wavelength:

$$\lambda = \frac{h}{\Delta E} \cdot c = 21.106 \text{ cm}$$

This is often called "21 cm" emission or absorption.

Emission or absorption from ionized hydrogen (HII) is another important probe of the ISM.

Consider that any UV photon with a wavelength shorter than 912 Å can ionize neutral hydrogen from the ground state. We already know of examples of sources which emit a significant number of UV photons, O and B stars. Often these stars (in regions of active star formation) are found in what are called HII regions, regions with a significant number density of HII. These HII regions are often spherical. These spherical regions are sometimes called Strömgren spheres.

The site of a Strömgren sphere around a source of UV photon emission can be easily calculated. If the source emits N_γ UV photons, this must be balanced by an equal number of HII → HI recombinations:

$$N_\gamma = \frac{4}{3}\pi R_s^3 \underset{\text{recombination coefficient}}{\alpha} \overbrace{n_p n_e}^{\text{\# densities of } e^- \text{ and } p}$$

Note that we have assumed the HII region is optically thick to UV photons. To understand the kind of emission we expect to see from HII regions, astronomers consider two scenarios:

① Case A Recombination

② Case B Recombination

Case A recombination assumes the nebula is optically thin to all transitions from $n \geq 2 \Rightarrow n=1$ state. In this case, we would expect a large number of Lyman series photons, also with UV wavelengths.

Case B (the more physically relevant scenario) assumes the nebula is optically thick to the Lyman series photons. In this case the UV line photons are quickly reprocessed and emitted as higher order lines, e.g. $H\alpha$ and $H\beta$ (Balmer lines). As a result HII regions are very bright in $H\alpha$ and often appear "red".

Finally, we can not neglect emission from dust. Dust grains are heated when absorbing photons. Depending on the environment, dust may have temperatures between $\sim 10 - 1000$ K. Therefore, we expect the majority of dust to emit in the infrared. Although the size distribution of dust grains is thought to be roughly a power law,

$$N(a) \propto a^{-\beta}$$

grain size

Roughly the contribution can be broken up into 3 components

- small ($\lesssim 100$ Å)
- large (> 100 Å)
- PAHs